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ORIGINAL ARTICLE

Influences of climate on fire regimes in montane forests of north-western Mexico

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ABSTRACT

Aim To identify the influence of interannual and interdecadal climate variation on the occurrence and extent of fires in montane conifer forests of north-western Mexico.

Location This study was conducted in Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.)-dominated mixed-conifer forests in the central and northern plateau of the Sierra San Pedro Mártir, Baja California, Mexico.

Methods Fire occurrence was reconstructed for 12 dispersed sites for a 290-year period (1700–1990) from cross-dated fire-scarred samples extracted from live trees, snags and logs. Superposed epoch analysis was used to examine the relationships of tree-ring reconstructions of drought, the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) with fire occurrence and extent.

Results Years with no recorded fire scars were wetter than average. In contrast, years of widespread fires were dry and associated with phase changes of the PDO, usually from positive (warm) to negative (cold). The influence of the PDO was most evident during the La Niña phase of the ENSO. Widespread fires were also associated with warm/wet conditions 5 years before the fire. We hypothesize that the 5-year lag between warm/wet conditions and widespread fires may be associated with the time necessary to build up sufficient quantity and continuity of needle litter to support widespread fires. Two periods of unusually high fire activity (1770–1800 and 1920–1950) were each followed by several decades of unusually low fire activity. The switch in each case was associated with strong phase changes in both PDO and ENSO.

Main conclusions Climate strongly influences fire regimes in the mountains of north-western Mexico. Wet/warm years are associated with little fire activity. However, these years may contribute to subsequent fire years by encouraging the production of sufficient needle litter to support more widespread fires that occur in dry/cool years.

Keywords

Climate variability, conifer forest, dendrochronology, ENSO, fire ecology, fire regime, Jeffrey pine, landscape ecology, Pacific Decadal Oscillation, *Pinus jeffreyi*.

INTRODUCTION

Fire regimes (i.e. fire frequency, return intervals, extent and season) have been shown to vary over space and time at many scales (Taylor & Skinner, 1998, 2003; Heyerdahl *et al.*, 2001; Whitlock *et al.*, 2003). These variations have often been associated with variations in climate. Widespread fires are generally associated with dry years that are produced by phasing patterns of global and regional scale climate-forcing mechanisms [e.g. El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO); Swetnam & Betancourt, 1990, 1998; Kitzberger *et al.*, 2001, 2007; Heyerdahl *et al.*,

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2002; Schoennagel *et al.*, 2005; Taylor & Beaty, 2005]. Developing a better understanding of the temporal and spatial connections between fire and various climate-forcing mechanisms at annual to decadal scales, especially during this period of rapidly changing climate, would help managers to better plan fire management activities and the use of suppression and prescribed fire resources.

Fire activity in areas under the influence of the North American Monsoon System (NAMS; Swetnam & Betancourt, 1990, 1998) and the Pacific Northwest Maritime Climate (PNW) has been shown to be related to the ENSO (Heyerdahl *et al.*, 2002; Hessl *et al.*, 2004). However, the influence in the two regions is in opposite directions. While dry years with widespread fires are associated with La Niñas in the NAMS, El Niños are associated with dry years of widespread fires in the PNW. Within the North American mediterranean climate area, the relationship between ENSO and years of widespread fires is not as pronounced as in the NAMS (Norman & Taylor, 2003; Taylor & Beaty, 2005). Although years with heightened fire activity are still associated with unusually dry conditions in this climate region (Norman & Taylor, 2003; Stephens *et al.*, 2003; Keeley, 2004; Stephens & Collins, 2004; Taylor & Beaty, 2005), these years were not found to be strongly associated with ENSO (Norman & Taylor, 2003; Keeley, 2004; Taylor & Beaty, 2005).

Along the west coast of North America, the PDO (variation in sea surface temperatures of the northern Pacific Ocean) is an important driver of climatic variation (Mantua & Hare, 2002). Warm (cool) phases of the PDO are associated with dry (wet) periods in the PNW with the inverse of these associations found in the south-western USA (Mantua & Hare, 2002). Historical fire activity in the PNW (Hessl *et al.*, 2004), the North American mediterranean climate area (Norman & Taylor, 2003; Taylor & Beaty, 2005) and the Rocky Mountains (Schoennagel *et al.*, 2005), as well as present-day fire occurrence patterns (Trouet *et al.*, 2006), are apparently related to variation in the PDO. ENSO varies on an interannual scale (2–7-year frequency; Allan, 2000), while the PDO oscillates on a lower, decadal frequency (15–25 years; Mantua & Hare, 2002). It appears that the effects of PDO and ENSO on climate along the west coast of North America interact, emphasizing each other's influence (constructive) when in phase, and reducing each other's influence (destructive) when out of phase (Biondi *et al.*, 2001; Mote *et al.*, 2003). Thus, years associated with heightened fire activity appear to result from complex interactions between the phasing of ENSO and PDO in the North American mediterranean climate area (Norman & Taylor, 2003; Taylor & Beaty, 2005) and the Rocky Mountains (Schoennagel *et al.*, 2005).

In both the US south-west and mediterranean climate areas, years with widespread fire activity have been shown to be associated with wetter than average conditions in the several years immediately preceding the fire year (Swetnam & Betancourt, 1998; Norman & Taylor, 2003; Swetnam & Baisan, 2003; Taylor & Beaty, 2005). This association with antecedent wet years is understood to be due to the increased productivity of herbaceous vegetation, responding to the high moisture availability. This increase in productivity is believed to lead to rapid accumulation of flashy fuels that are easily ignited and readily carry fire during the subsequent drier years (Swetnam & Betancourt, 1998). Southern California is an exception, with the length of the current-year dry season and the annual occurrence of strong, dry foehn winds (Santa Ana's) more important than antecedent climate conditions (Keeley, 2004). Understanding how antecedent conditions influence years with widespread fires is important in developing the capacity to predict such years accurately.

Intensive fire exclusion in the western USA has generally caused widespread alteration of fire regimes over the last century or so (Agee, 1993; Skinner & Chang, 1996; Swetnam & Baisan, 2003). Thus, studies that rely on tree-ring reconstructions of fire regime characteristics are generally restricted to describing fire/climate interactions before the beginning of effective fire exclusion (Swetnam & Betancourt, 1998; Taylor & Skinner, 1998, 2003; Heyerdahl *et al.*, 2001; Norman & Taylor, 2003; Taylor & Beaty, 2005). In contrast, the montane conifer forests of Mexico have often not experienced intensive fire exclusion (Baisan & Swetnam, 1995; Fulé & Covington, 1998, 1999; Minnich *et al.*, 2000a; Heyerdahl & Alvarado, 2003; Stephens *et al.*, 2003). Thus, the fire-scar record extends to the present in many of these forests, and they may provide important information on fire–climate associations that is unavailable in the western USA.

With the exception of studies in northern Baja California (Minnich *et al.*, 2000a; Stephens *et al.*, 2003), tree-ring-based fire histories from Mexico are from locations clearly under the strong influence of the NAMS (Fulé & Covington, 1998, 1999; Heyerdahl & Alvarado, 2003), and these records have demonstrated a relationship between ENSO and fire activity. Although Stephens *et al.* (2003) found an association between fire and drought in the two sites they studied, no clear association emerged between fire activity and teleconnections with ENSO or PDO. Perhaps the spatially limited geographical context of the Stephens *et al.* (2003) study, confined to the central plateau of the Sierra San Pedro Mártir (SSPM), hindered the detection of any association of fire activity with ENSO or PDO.

In this paper we expand our study area to 12 dispersed sites of montane conifer forests in the SSPM to examine fire–climate relationships in the North American mediterranean climate area not yet strongly influenced by intensive fire suppression activities. Our objectives were to address the following questions: (1) How has fire occurrence and extent varied over time? (2) Are variations in fire regime characteristics (fire occurrence, season and extent) associated with individual or combinations of proxy indicators of climate (e.g. ENSO, PDO)? (3) Have the influences of climate on fire regimes been stable or variable over time? (4) Were antecedent conditions necessary for widespread fires or were they responding simply to current-year conditions? (5) How did 20th century fire regime characteristics compare with those of previous centuries?

STUDY AREA

The study area is located in the SSPM, *c.* 100 km south-east of Ensenada, Baja California, Mexico (Fig. 1). The SSPM is a southern component of the Peninsular Ranges, which extend *c.* 350 km to the north and terminate in the San Jacinto Mountains in California, USA. Although the highest peaks of the SSPM reach heights of over 3000 m, elevation generally ranges from *c.* 2600 m above sea level (a.s.l.) in the north to 1800 m a.s.l. in the south. Soils are derived primarily from granitic parent material with inclusions of metamorphic quartz schists (Stephens & Gill, 2005). The conifer forests of the SSPM have experienced neither tree harvesting nor long-term, intensive fire suppression. However, since the mid-1970s there has been limited fire suppression consisting of one or two four-person hand crews in the summer and autumn periods.

The vegetation of the SSPM includes conifer forests and shrublands of the Californian floristic province (Minnich *et al.*, 1995; Minnich & Franco-Vizcaíno, 1998). Conifer forests cover *c.* 40,655 ha of the SSPM (Minnich *et al.*, 2000a). The most common forest types are Jeffrey pine [*Pinus jeffreyi* Grev. & Balf. (nomenclature follows Hickman, 1993)], Jeffrey pine–mixed conifer and mixed white fir [*Abies concolor* (Gordon & Glend.) Lindley] forests, respectively (Minnich & Franco-Vizcaíno, 1998). While Jeffrey pine dominated all sampled sites, other conifers co-occurred, e.g. white fir, sugar pine (*Pinus lambertiana* Douglas), incense-cedar [*Calocedrus decurrens* (Torrey) Florin] and lodgepole pine (*Pinus contorta* var. *murrayana* Dougl. ex. Loud.). Although the conifer forests are quite variable in structure and age classes, they are generally more open, and with fewer small trees and more old trees than in similar forests found in California (Barbour *et al.*, 2002; Stephens & Gill, 2005). Additionally, surface fuel loads are much more patchy and discontinuous than in mixed conifer forests of the Sierra Nevada (Stephens, 2004). These differences are probably due to the relatively minor impact of management activities on the fire regime in the SSPM, contrasted with a century of fire exclusion and intensive forest management in the USA (Stephens & Fulé, 2005).

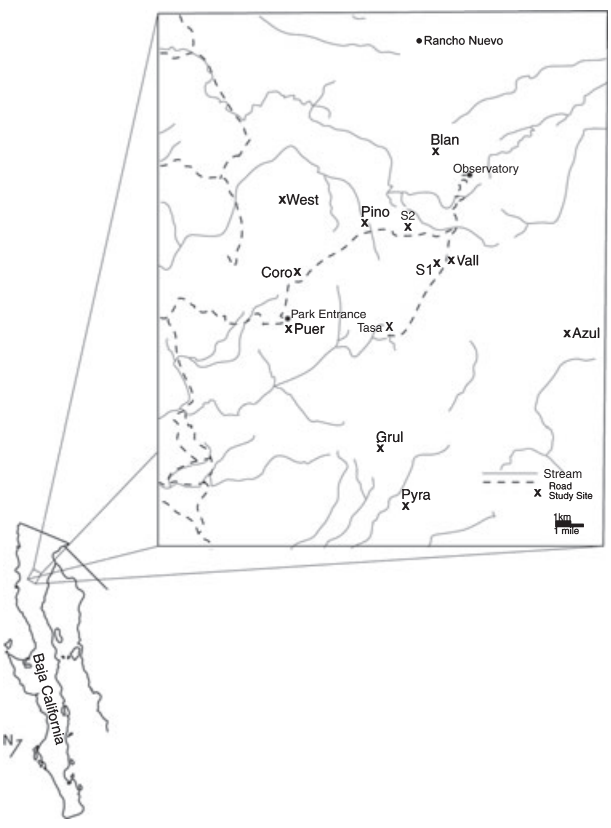

Figure 1 Map of the study area.

The SSPM is described as having a mediterranean-type climate (Markham, 1972; Pyke, 1972; Reyes Coca *et al.*, 1990; Minnich *et al.*, 2000a). Annual precipitation at Vallecitos Meadow averaged 55 cm from 1989–1992 (Minnich *et al.*, 2000a). However, weather data are limited in the SSPM because of its remoteness.

METHODS

Fire occurrence and extent

We collected fire-scarred wedges and cross-sections of conifers from 12 sites dispersed across the SSPM. Two sites (S1 and S2) have been described by Stephens *et al.* (2003). The 10 additional sites (Burk, 1991) from the northern and central SSPM were located to represent the geographical distribution of the Jeffrey pine-dominated mixed conifer forests; they varied from 4 to *c.* 20 ha in size and ranged in elevation from *c.* 2000 to 2600 m a.s.l. (Fig. 1). While most fire-scarred specimens were collected from Jeffrey pine, several specimens each were collected from white fir, sugar pine and incense-cedar.

Sampling on each site was designed to maximize the completeness of fire occurrence dates over as long a time period as possible. We systematically located fire-scarred specimens, examining each live tree, log and snag observed to contain fire scars. We then collected samples from specimens with the greatest numbers of well-preserved fire scars distributed as broadly as possible across the site (Swetnam & Baisan, 2003; Van Horne & Fulé, 2006). Although all fires on a site may not have created scars, the sampling pattern allowed us to distinguish years of little or no fire activity from those of more extensive fire activity (Taylor & Skinner, 2003; Taylor & Beaty, 2005; Van Horne & Fulé, 2006).

Each wedge or cross-section used to document fire scars was sanded and polished to a high sheen and then cross-dated with a local tree-ring chronology (Stokes *et al.*, 1973) obtained from the International Tree-ring Data Bank (ITRDB), using standard dendrochronological techniques (Stokes & Smiley, 1968; Swetnam *et al.*, 1985). Those specimens that could not be visually cross-dated were cross-dated using the program COFECHA (Grissino-Mayer, 2001a). Only successfully cross-dated samples were used for determining fire-scar dates. Those that could not be cross-dated, usually due to severely slow

growth with many missing rings, were not used in analyses. FHX2 software was used to store and analyse fire-scar data (Grissino-Mayer, 2001b).

To investigate the extent of annual fire activity, we determined the year and number of fires that burned in ≥ 1, ≥ 2 and up to ≥ 6 of the 12 sites for all fires and for fires scarring two or more trees at a site. To detect periods of rapidly changing fire regimes, we smoothed the fire occurrence record by summing over a 25-year moving window in two ways: (1) the number of years a fire was recorded on any SSPM study site as a representative of fire occurrence, and (2) the number of sites recording fires as a representation of fire extent (Taylor & Beaty, 2005). We selected the 25-year window, as it is roughly equivalent to half the cycle of the PDO (Mantua & Hare, 2002). The results were then normalized about zero so they could be displayed on charts with each other and the climate indices.

We used a fire activity index (FAI) that is similar in concept to fire rotation, with some important differences. Fire rotation is defined as the number of years required to burn an area equivalent to that of the study area given the extent of burning in the defined period (Heinselman, 1973). In any given period, some sites may have burned more than once and others not at all. Since the sample sites are widely separated in this study, instead of fire rotation, we define the FAI as the number of years required to scar trees on 12 of our sample sites where, in any given period, some sites may have burned more than once and others not at all. We make no assumptions about the degree of continuity of fires among the widely dispersed sites. Temporal variation of the FAI was determined by summing the number of sites burned in a 25-year moving window, followed by calculating the number of years necessary to burn all 12 sites. We counted a site as burned if two or more trees were scarred in a year.

Fire/climate interactions

The season of occurrence for each fire was estimated from the intra-ring position of each scar, noted as EE (early earlywood), ME (middle earlywood), LE (late earlywood), LW (latewood), D (dormant or ring boundary) or U (undetermined; Caprio & Swetnam, 1995). At this latitude in western North America, dormant season scars usually represent fires burning in the early spring or late winter, before the onset of tree growth (Ahlstrand, 1980; Dieterich & Swetnam, 1984; Stephens *et al.*, 2003). Within the North American mediterranean climate area, intra-ring scar position varies from ring-boundary scars, most common in the Klamath Mountains of northern California, to within-ring scars, most common in the southern Sierra Nevada (Skinner, 2002; Stephens & Collins, 2004), to mostly latewood and ring-boundary scars in southern California (Everett, 2003; Skinner *et al.*, 2006). Since the SSPM was found to have a predominance of earlywood scars (Stephens *et al.*, 2003), it was necessary to compare each dormant-season scar with fire scars in the rings of other trees in flanking years in order to assign the probable year of the fire. We further confirmed our interpretation of timing of historical fires from the tree-ring record by collecting wedges and determining the intra-ring locations of scars from 10 trees within an area that burned in the study area on 4 July 2003.

Superposed epoch analysis (SEA) was used to examine the interannual relationship between fire occurrence and six proxy climate indices (Baisan & Swetnam, 1995; Grissino-Mayer & Swetnam, 2000): South-western Drought Index (SWD; Cook, 2000a), two indices of ENSO (NINO3, Cook, 2000b; SOI, Stahle *et al.*, 1998), three indices of PDO (PDO_B, Biondi *et al.*, 2001; PDO_D, D'Arrigo *et al.*, 2001; PDO_M, MacDonald & Case, 2005), and western North American regional summer temperature index grid point latitude 30° N, longitude 110° W (ST; Briffa *et al.*, 2002). The SEA compares proxy climate indices reconstructed from tree rings with fire dates by superposing windows of concurrent and lagged climatic conditions for each fire year. Monte Carlo simulations (1000 runs) were used to develop confidence intervals to determine whether climate was significantly different from average during, immediately before, and after fire years (−6/+4 years; Swetnam & Baisan, 2003). For the SEA, we used years in which three or more of the 12 sites (25%) had two or more trees scarred to represent years of more extensive fire activity.

We considered the PDO reconstructions by Biondi *et al.* (2001), D'Arrigo *et al.* (2001) (PDO_D) and that of MacDonald & Case (2005) (PDO_M). First, we considered Biondi *et al.* (2001) because the tree-ring chronologies used to develop the former index were from southern California, with one from northern Baja California, and are likely to represent the influence of the PDO on our study area. However, all of these chronologies were from drought-sensitive trees in the mediterranean climate area of southern California and northern Baja California. Therefore, we also compared fire occurrence with the PDO_D reconstruction of D'Arrigo *et al.* (2001) and PDO_M of MacDonald & Case (2005) because they were developed entirely or partly from tree-ring chronologies from areas under the influence of very different climates.

We used NINO3 instead of SOI for the remainder of this study since SOI was not found to be significantly associated with fire occurrence in the SSPM using the filter of multiple trees scarred on three or more sites in a year. However, since SOI has been found to be related to precipitation variability in the contemporary record (Minnich *et al.*, 2000b) we tested for an SOI relationship with fire using a more relaxed filter of ≥ 10% of sampled trees scarred in a year. The SOI was found to be associated with fires using this filter. This was considered a more relaxed filter because it could be met with fires burning on only one of the sites. The NINO3 is derived from a grid of sea surface temperature (SST) sensors in a region of the Pacific Ocean (5° N–5° S, 150° W–90° W; Trenberth, 1997) that captures the greatest variability in interannual SST associated with the ENSO (Schoennagel *et al.*, 2005). The SOI is derived from the difference in sea level pressures between two locations, Tahiti (17.5° S, 149.6° W) and Darwin, Australia (12.4° S, 130.9° E; Trenberth & Caron, 2000). While the two indices are strongly correlated, they are periodically out of

phase with each other (McCabe & Dettinger, 1999). It may be that the NINO3 index has a stronger association with the SSPM fire occurrence than SOI because our study area is closer to the NINO3 region and the NINO3 region captures the greater variation in SST associated with ENSO.

To investigate decadal associations graphically, we smoothed the annual variation by calculating a weighted 10-year moving average for each climate index and then normalized the results so they could be compared on a common scale. A similar smoothing was used for two representations of fire occurrence: (1) number of years in which a fire occurred anywhere in the SSPM in the 10-year window, and (2) a 10-year window of the number of sites recording fires. A site was counted each year it recorded a fire in two or more trees.

To assess the potential combined influence of PDO and ENSO on the fire regime, we added the values of PDO_B and NINO3 for each year (PDO_B + NINO3; Biondi *et al.*, 2001; Mote *et al.*, 2003) and then normalized the results about zero. When these indices are combined in this way, the higher/lower absolute values are higher/lower during constructive/destructive interference between PDO and ENSO (Biondi *et al.*, 2001; Mote *et al.*, 2003). We then smoothed this combined index with the weighted 10-year average (as described above) to compare with fire occurrence patterns.

RESULTS

Fire occurrence and extent

Fire record

In total, 257 specimens with 1816 fire scars were cross-dated from the 12 sites (Table 1). We used the period of AD 1700–1990 for our subsequent analyses since several sites lacked samples extending much before 1700 (Fig. 2).

Table 1 The number of cross-dated fire-scar samples, total fire scars and time period spanned by the fire-scar record for each collection site.

Site	Samples cross-dated	Fire scars	Scars per sample	Earliest ring	Earliest scar	Last scar
Blan	6	38	6.3	1571	1626	1938
West	23	161	7.0	1558	1600	1981
Pino	16	93	5.8	1487	1722	1959
S2	52	511	9.8	1464	1521	1962
S1	53	523	9.9	1473	1527	1980
Vall	19	79	4.2	1553	1688	1973
Coro	14	85	6.1	1477	1601	1963
Puer	14	70	5.0	1676	1740	1946
Tasa	12	39	3.3	1569	1654	1965
Azul	18	73	4.1	1548	1587	1956
Grul	15	82	5.5	1650	1669	1966
Pyra	15	62	4.1	1693	1752	1956

Sites are ordered from north to south.

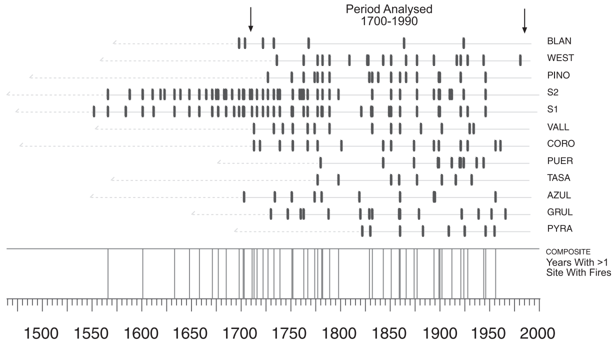

Figure 2 Composite fire activity for the 12 sample sites in the Sierra San Pedro Mártir. Each horizontal line is a sample site and each vertical dash is a fire that scarred two or more trees in the year at that site. Sites are ordered from north to south.

Fire season

We were able to determine the intra-annual ring position of the fire scars for 1425 (79%) of the scars. Of these scars, 94% were in earlywood (EE 52%, ME 28%, LE 13%) with 6% in latewood and only four ring-boundary scars. The distribution of scars by ring position varied among the sites (Table 2) and over time (Fig. 3).

The wedges taken from 10 trees in the 4 July 2003 fire all had considerable bark char and appeared to have been scarred by the fire. The intra-ring position of fire scars in these 10 samples were distributed as follows: ME = 3, LE = 3, no 2003 scar = 4.

Fire occurrence and extent

There was no single year in which fires scarred at least one tree on all 12 sites (Table 3). The most sites with at least one tree scarred in a single year was eight in 1767. Sixteen years had six or more sites with at least one tree scarred (Table 3). Years in

Table 2 Intra-ring position of fire scars by collection site.

Site	Fire scars	Scars with Season	Intra-ring position %D	%EE	%ME	%LE	%LW
Blan	38	29	0.0	37.9	48.3	13.8	0.0
West	161	142	0.0	51.4	25.4	16.2	7.0
Pino	93	73	0.0	54.8	32.9	11.0	1.4
S2	511	369	0.0	52.3	29.3	10.8	7.6
S1	523	416	1.0	42.1	31.5	16.1	9.4
Vall	79	67	0.0	52.2	32.8	13.4	1.5
Coro	85	71	0.0	73.2	16.9	8.5	1.4
Puer	70	67	0.0	82.1	9.0	7.5	1.5
Tasa	39	30	0.0	36.7	43.3	20.0	0.0
Azul	73	49	0.0	73.5	18.4	8.2	0.0
Grul	82	61	0.0	54.1	26.2	18.0	1.6
Pyra	62	51	0.0	62.7	15.7	13.7	7.8

Sites are ordered from north to south. Intra-ring position is the percentage of fire scars found by ring position. Ring position is indicated by D (dormant or ring boundary), EE (early third of earlywood), ME (middle third of earlywood), LE (late third of earlywood) and LW (latewood).

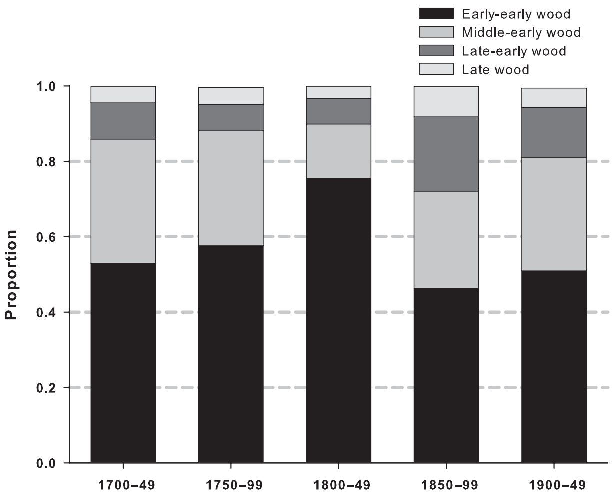

Figure 3 Cumulative proportion of intra-ring position of fire scars by 50-year periods for all 12 sites combined.

Table 3 Fire return interval statistics for fires scaring at least one tree per site for the period 1700–1990.

No. sites	No. intervals	Median interval	Mean interval	Range	Standard deviation	Skew
1	157	1	1.78	1–9	1.21	2.48
2	68	3	3.87	1–18	3.46	1.76
3	35	5	7.26	1–31	6.24	1.80
4	27	7	9.00	1–43	8.64	2.33
5	21	10	11.57	1–43	9.76	1.48
6	15	17	16.2	1–43	10.50	0.89

No. sites, number of sites with at least one tree scarred in the same year.

Table 4 Fire return interval statistics for fires scarring two or more trees per site for the period 1700–1990.

No. sites	No. intervals	Median interval	Mean interval	Range	Standard deviation	Skew
1	88	2	3.17	1–15	2.65	1.81
2	38	6	6.68	1–31	5.73	2.18
3	24	7	10.13	1–43	9.14	2.01
4	14	14	15.21	4–43	10.50	1.21
5	8	18	19.75	9–43	10.47	1.33
6	2					

No. sites, number of sites with two or more trees scarred in the same year.

which ≥ 10% of trees were scarred on each of ≥ 50% of sites were 1777, 1832, 1851, 1860 and 1921. However, only 3 years had six or more sites with two or more trees scarred (Table 4). Years in which at least two trees were scarred on individual sample sites are shown in Fig. 2.

The fire activity index (FAI) varied between *c.* 15 and 25 years for much of the period of analysis. However, in the early decades of the 1800s the FAI was as long as 100 years and in the later 20th century was > 50 years (Fig. 4).

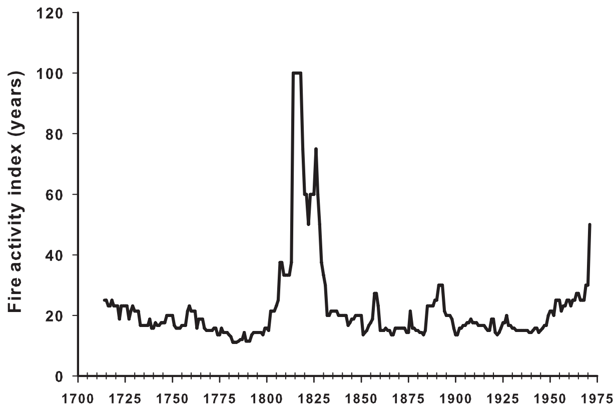

Figure 4 Variation in fire activity index (FAI) over time or the time required to burn the equivalent of 12 sites based on the extent of burning in a 25-year moving window plotted in the central year of the window.

Temporal variability

Two periods of high fire activity, both followed by periods of low fire activity, are evident: 1775–1800 exhibited the most extensive fires and 1915–1950 exhibited the most frequent fires (Fig. 5). The two periods of low fire activity are 1805–1830 and the most recent few decades (Fig. 5). In these periods of low fire activity, both the extent and frequency of fires were low.

Fire/climate interactions

Interannual relationships

The superposed epoch analysis indicated that years in which the more extensive fires occurred were dry, as indicated by significantly negative SWD ($P \le 0.01$; Fig. 6a). Additionally, the significantly positive SWD indicates that the fifth year before a fire year was relatively wet ($P \le 0.05$). Non-fire years (years in which none of the sample specimens on any of the 12 sites were scarred) were associated with wetter than average conditions, as indicated by positive SWD ($P \le 0.05$; Fig. 7a).

The dry years of more extensive fires were associated with a negative NINO3 index ($P \le 0.05$; Fig. 6b). However, the years of more extensive fire were not found to be associated with antecedent conditions of the NINO3 index. For non-fire years, the NINO3 showed a significant association with positive index values (wet) for the year that was 2 years before the non-fire year ($P \le 0.05$), but no association with the non-fire year itself (Fig. 7b).

The dry years in which fires occurred took place when the PDO was shifting phase, mostly from positive to negative. The years leading up to fires had significantly higher values of PDO than average (positive phase) [years −6: $P \le 0.05$ (PDO_B, PDO_M) and −5: $P \le 0.05$ (PDO_B, PDO_D, PDO_M)], the year of the fire not significantly different than average PDO (PDO_B, PDO_D, PDO_M) and the years following fires significantly lower than average PDO values (negative phase) [year 1: $P \le 0.01$ years 2–4: $P \le 0.05$ (PDO_B)] (Fig. 6c–e). PDO_M

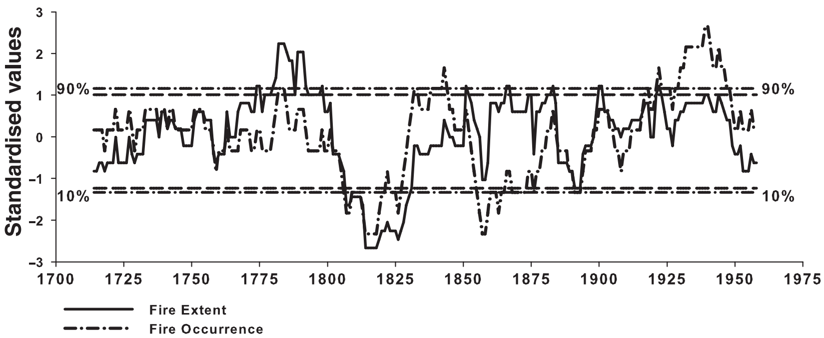

Figure 5 Moving 25-year windows of fire activity plotted in the central year of the window. Fire occurrence is based on the number of years with fires and fire extent is based on the number of sites burned in the window. The 10th and 90th percentiles for each are shown. Each variable has been normalized about zero for charting on a common graph.

showed a non-significant decline from the positive conditions before the fire year to a negative condition following the fire year. No significant association was found with non-fire years and the PDO except that PDO_B was in a positive phase ($P \leq 0.05$) the year following the non-fire year and PDO_M in the second year after the non-fire year (Fig. 7c–e). The only significant interannual temperature relationship was for warm years to occur 1 year before a non-fire year (Fig. 7f).

Interdecadal relationships

Fire occurrence as well as the number of sites burning synchronously varied over time (Fig. 5). Several prominent peaks and troughs of fire occurrence are evident in the data. Fire occurrence tended to increase in negative phases of the combined PDO_B + NINO3 and diminish during the positive phases (Fig. 8).

DISCUSSION

Climate and fire season

The conifer forests of the SSPM are described as being in the North American mediterranean climate area (Markham, 1972; Pyke, 1972; Reyes Coca *et al.*, 1990; Minnich *et al.*, 2000a). However, over 90% of the fire scars were found in the earlywood portion of the rings (Fig. 2). This predominance of fire scars in earlywood is quite different from the pattern found in other portions of the mediterranean climate area of the North American Pacific Coast, where fire scars are more commonly found in latewood and at the ring boundary (Stephens *et al.*, 2003) even as far south as the Transverse and Peninsular ranges of southern California (Everett, 2003; Skinner *et al.*, 2006). The intra-ring position of fire scars in earlywood in the SSPM suggests that most fires are likely to have burned in the spring to early summer (Stephens *et al.*, 2003). The samples gathered from trees scarred by a large fire on 4 July 2003 are also in earlywood, as would be expected.

We hypothesize that the reason for the earlywood fire scars is because the SSPM is not as strongly under the influence of the mediterranean climate as lower-altitude coastal areas (e.g. Ensenada) or California to the north. The timing of fire occurrence in the SSPM is similar to that found in Arizona, New Mexico, and northern Mexico (Grissino-Mayer & Swetnam, 2000; Swetnam *et al.*, 2001; Heyerdahl & Alvarado, 2003) under the influence of the North American Monsoon System (NAMS).

The North American mediterranean climate area and the NAMS have strongly different precipitation regimes (North American mediterranean climate area, summer dry; NAMS, summer wet), and one would expect that the timing of fires would differ between them. Interactions of the ENSO and PDO have been found to affect precipitation patterns in both the North American mediterranean climate area (Biondi *et al.*, 2001) and the NAMS (Castro *et al.*, 2001). Importantly, interactions of the ENSO and PDO help determine the annual onset and spatial boundaries of the NAMS (Minnich *et al.*, 2000b; Castro *et al.*, 2001). Additionally, eastern Pacific tropical storms affect Baja California more frequently than other mediterranean climate areas further north (Higgins & Shi, 2005; Larson *et al.*, 2005). The altitude and latitudinal position of the SSPM may combine to influence warm season moisture associated with the NAMS (Minnich *et al.*, 1993, 2000b; Stephens *et al.*, 2003; Higgins *et al.*, 2004) and eastern Pacific tropical storms (Minnich *et al.*, 1993; Higgins & Shi, 2005; Larson *et al.*, 2005). We hypothesize that the influence of these two phenomena affects the seasonality of fires, so that we find the predominance of earlywood fire scars in the SSPM instead of the preponderance of latewood and ring-boundary scars typical of that found in the mediterranean forests of California.

It has been suggested that the dominance of fires in the earlywood in the SSPM may be strongly influenced by human-caused fires (Evett *et al.*, 2007a). Although there is no evidence of human use of fires in the SSPM, before the 20th century native people used fire widely in the shrublands below the SSPM conifer forests (Meigs, 1935). The SSPM plateau was not permanently inhabited before the establishment of the Spanish mission in the 1790s, but was used seasonally in the summers (Meigs, 1935). More recently, the fire of 4 July 2003 is believed to have been a human-caused fire that started in chaparral below the SSPM plateau and made its way up the western escarpment into the conifer forests. There also appears to be a discrepancy between the number of fires recorded in the tree rings as early-season fires and the potential for lightning-caused ignitions at that time of the year (Minnich *et al.*, 1993; Evett *et al.*, 2007a). However, whether ignited by lightning or humans, the ability of the fires to burn would be hindered by precipitation and the high relative humidity associated with

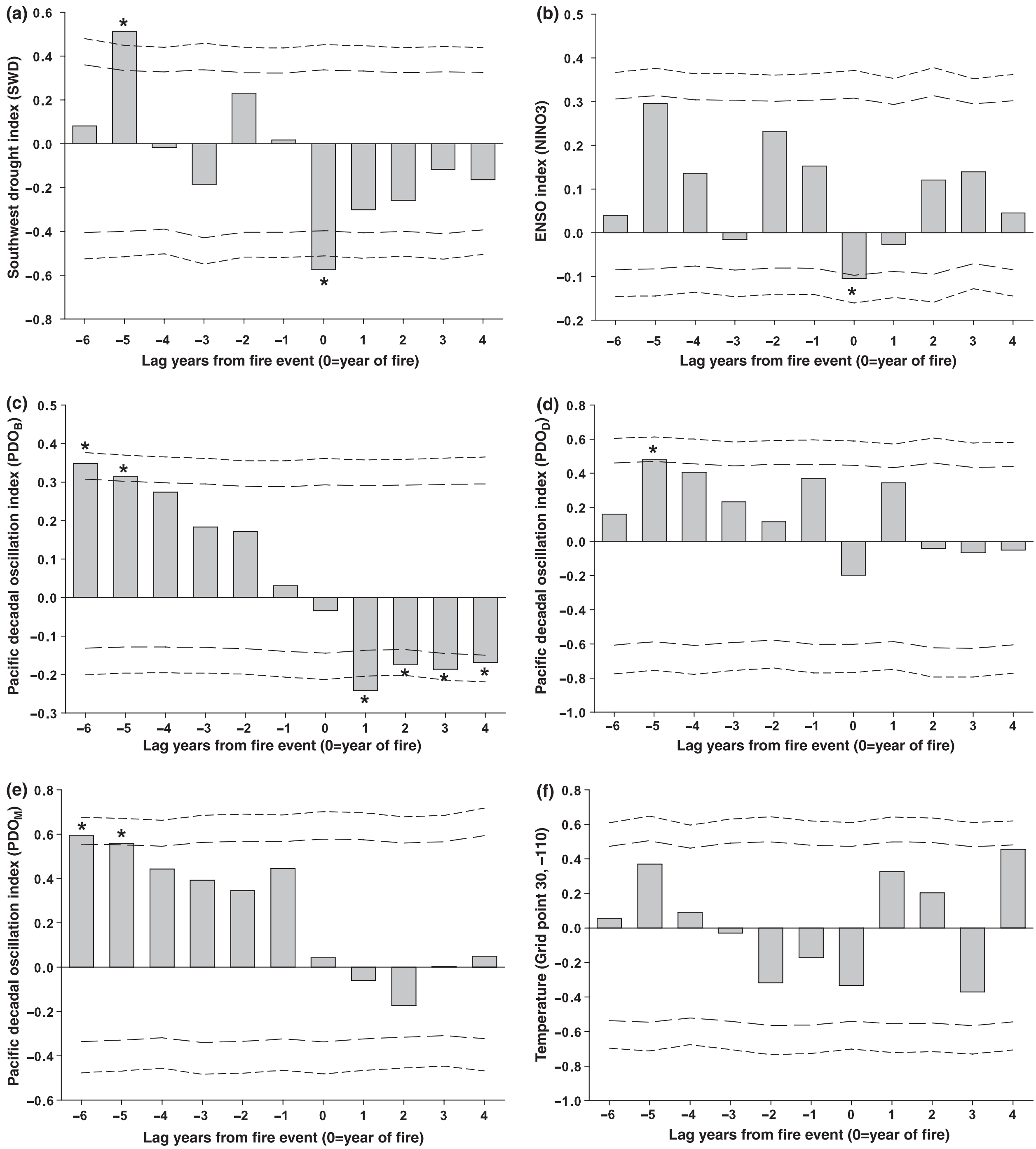

Figure 6 Superposed epoch analyses (SEA) of (a) South-western Drought Index SWD (Cook, 2000a), (b) El Niño/Southern Oscillation index NINO3 (Cook, 2000b), (c) Pacific Decadal Oscillation index PDO_B (Biondi *et al.*, 2001), (d) PDO_D (D'Arrigo *et al.*, 2001), (e) PDO_M (MacDonald & Case, 2005), and (f) summer temperature (Briffa *et al.*, 2002) with years when fires scarred two or more trees on three or more sites from 1700–1990 across the Sierra San Pedro Mártir study area. Bars with values significantly different from the mean are shown with an asterisk.

mid–late summer thunderstorms (cf. Minnich *et al.*, 1993, 2000b). We suggest that if the climate of the SSPM were simply an extension of the southern California mediterranean climate, there would be a greater proportion of scars found in latewood, similar to that found in southern California.

Climate dynamics

Climatic variability at multiple temporal and spatial scales has strongly influenced the occurrence and extent of fires in the conifer forests of the SSPM over the last several centuries.

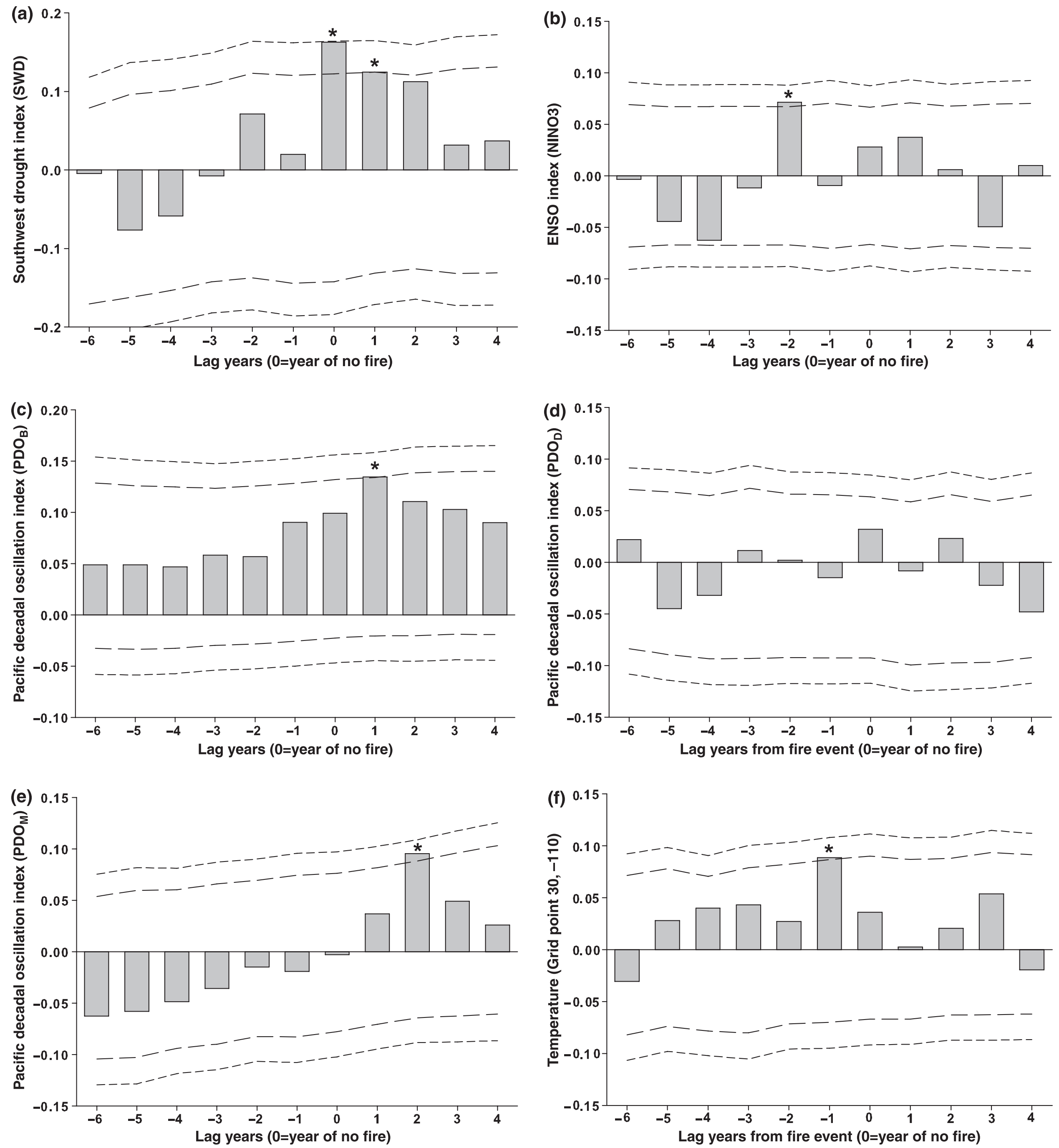

Figure 7 Superposed epoch analyses (SEA) of (a) South-western Drought Index SWD (Cook, 2000a), (b) El Niño/Southern Oscillation index NINO3 (Cook, 2000b), (c) Pacific Decadal Oscillation index PDO_B (Biondi *et al.*, 2001), (d) PDO_D (D'Arrigo *et al.*, 2001), (e) PDO_M (MacDonald & Case, 2005) and (f) summer temperature (Briffa *et al.*, 2002) with years when no sample trees were scarred on any of the sampled sites from 1700–1990 across the Sierra San Pedro Mártir study area. Bars with values significantly different from the mean are shown with an asterisk.

Large swings in fire frequency and extent have occurred that make it difficult to easily characterize the fire regime for more than a few decades running.

The period of low fire activity that occurred from approximately the 1790s through to 1830, as noted by Stephens *et al.* (2003), is pronounced in our record of fires from the multiple sites across the SSPM (Figs 2, 4 & 5). Thus, for several decades very few localized fires and no extensive fires were found in the fire-scar record of this mountain range. This period coincides with major shifts in fire regimes noted across western North America (Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Veblen *et al.*, 2000; Heyerdahl *et al.*, 2002;

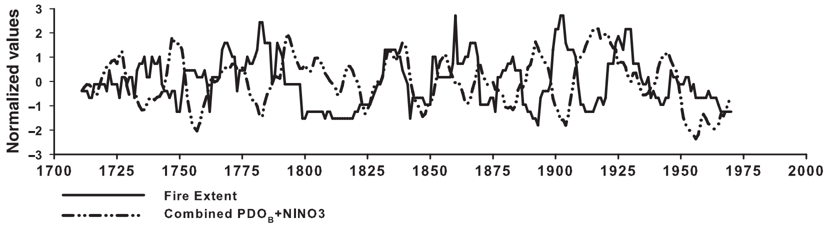

Figure 8 Decadal variation in fire extent (number of sites burned) in the Sierra San Pedro Mártir, and the combined Pacific Decadal Oscillation and El Niño/Southern Oscillation indices [PDO_B (Biondi *et al.*, 2001) plus NINO3 (Cook, 2000b)]. Each annual series was smoothed with a weighted mean over a 10-year moving window and normalized about zero for plotting relative changes on the same axis.

Norman & Taylor, 2003; Swetnam & Baisan, 2003; Taylor & Beaty, 2005) and South America (Kitzberger *et al.*, 2001). That the fire regime shifts were so widespread, although not always in the same direction, suggests a broad means of influence, such as climate (Kitzberger *et al.*, 2001). Accordingly, there was an apparent coincident shifting of several climatic factors into states that in combination did not support the occurrence of fires in many areas (Taylor & Beaty, 2005; Sibold & Veblen, 2006), the SSPM included. First, the PDO was primarily in an unusually cool phase during this period and lacked the strong oscillations of the previous several decades (Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001; Gedalof & Smith, 2001). Second, there was a rapid and prolonged decline in temperature (Jacoby & D'Arrigo, 1989; Briffa *et al.*, 1992; Graumlich, 1993; Dunbar *et al.*, 1994). Third, the amplitude of the ENSO signal weakened during this period (Anderson, 1992), and this has been associated with hemispheric disruption of fire regimes (Kitzberger *et al.*, 2001).

Temporal variation in the extent of fires is partially explained by the interaction of the PDO and ENSO (as portrayed here by the PDO_B and NINO3 indices). In the SSPM, years of widespread fires happened during dry years that occurred when the PDO_B was changing phase, usually from positive to negative, coincident with a negative NINO3 (La Niña).

The association of fire years with La Niña was supported by further testing using the $\delta^{18}O$ isotope measurements from the Palmyra corals (latitude 5.9° N, longitude 162.1° W: years 1886–1997; Cobb *et al.*, 2001) as another ENSO proxy. The amount of $\delta^{18}O$ in the coral skeletons varies with water temperature and precipitation (Lough, 2004). High values of $\delta^{18}O$ are associated with La Niña and low values with El Niño. We found strong correlation between the annual NINO3 tree-ring index and the December–January values of the Palmyra $\delta^{18}O$ ($r = -0.57$, $P < 0.001$). However, there was an insufficient number of fire years in the 1886–1997 period to conduct another SEA using the $\delta^{18}O$ data. Therefore, we used the chi-square test to assess the independence of fire years (represented by the number of trees scarred in a year) with contingent states of the normalized $\delta^{18}O$ data (< -0.5 = El Niño, -0.5 to 0.5 = average, > 0.5 = La Niña). While 34% of years were classified as La Niña in this way, 71% of the fire scars (376 of 530) were formed in La Niña years ($\chi^2 = 155.17$; $P < 0.001$; Fig. 9).

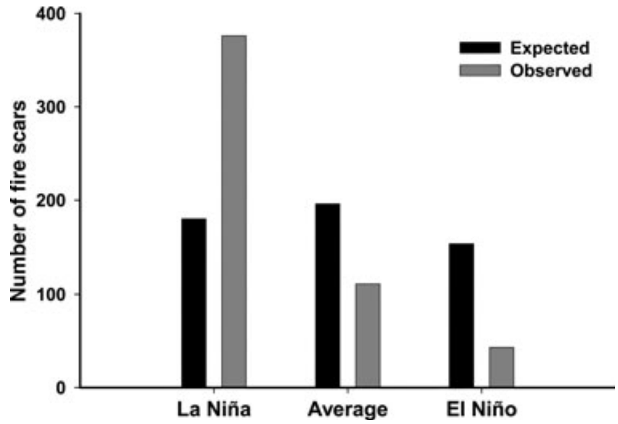

Figure 9 Occurrence of fire scars ($n = 530$) as a function of contingent states of the El Niño/Southern Oscillation (normalized Palmyra coral December–January $\delta^{18}O$ data: < -0.5 = El Niño, -0.5 to 0.5 = average, > 0.5 = La Niña) from 1886–1997.

The influence of the PDO/ENSO interaction has been discussed by others (Norman & Taylor, 2003; Hessl *et al.*, 2004; Schoennagel *et al.*, 2005; Taylor & Beaty, 2005), but the nature of the interaction has been different in each case. The interaction of PDO/ENSO/fire regime appears to shift along a latitudinal gradient. In interior Washington state (Hessl *et al.*, 2004) and the northern and central Rocky Mountains (Schoennagel *et al.*, 2005), widespread fires were found to be associated with dry years coincident with a positive PDO phase and El Niño. In the southern Cascades of northern California, Norman & Taylor (2003) found widespread fires to occur in dry years associated with the PDO changing phase from positive to negative, coincident with an El Niño. In the Lake Tahoe Basin of the Sierra Nevada, Taylor & Beaty (2005) found a decadal-scale association of extensive fires with PDO when the latter was changing phase from positive to negative coincident with a La Niña. However, the relationship with La Niña varied over time from strong during the 1700s to weak in the 1800s. In the southern Rocky Mountains, Schoennagel *et al.* (2005) found widespread fires associated with negative PDO and La Niña.

Since the PDO strongly influences climate in both the North American mediterranean climate area and the NAMS (Castro *et al.*, 2001) it should not be surprising that we detected a

strong interannual association with the PDO and widespread fires in the SSPM.

Climate and fuel

The significant association with wetter than average conditions 5–6 years before extensive fires is longer than the 1–4 years that has been reported for pine-dominated sites in the American southwest (Swetnam & Betancourt, 1998), the two sites previously studied in the SSPM (Stephens *et al.*, 2003), the southern Cascade Range (Norman & Taylor, 2003) or the Sierra Nevada (Stephens & Collins, 2004; Taylor & Beaty, 2005). These previous studies have suggested this association is probably due to increased fuels made available from the response of grasses and forbs to favourable climatic conditions. However, recent work has found a paucity of graminoid phytoliths in SSPM soil samples (Evett *et al.*, 2007b). Although a lack of graminoid phytoliths does not unconditionally establish a lack of significant grass cover in the SSPM understorey, it does suggest that grasses might not have contributed significantly to understorey fuel loads in the SSPM conifer forests during the centuries covered by this study (Evett *et al.*, 2007b). If there was such a lack of grass cover, another source of available fuel would be required. The most likely source of fuel that could respond to a 5–6 year window of favourable climate would be needles cast from the conifers. Jeffrey pine, the dominant conifer in most stands, retains needles for 4–6 years under favourable conditions (Rundel, 2002). Additionally, conifers have been shown to grow longer needles under favourable conditions (Fritts, 1965; McDonald *et al.*, 1992).

We propose that the 5–6 year lag between significantly positive PDO and SWD and years of extensive fires is a result of the time required to produce sufficient quantities of needle cast necessary to carry more extensive fires. The reliance on production of sufficient needle cast (Fig. 10) would also account for these forests having generally less frequent fires than mixed conifer or ponderosa pine (*Pinus ponderosa* Laws.) forests in more productive environments (e.g. the Sierra Nevada) or those where grasses are (or were) a significant component of the understorey (e.g. Arizona).

The spatially heterogeneous, patchy nature of these forests in a landscape with frequently exposed rocky areas results in fires that do not easily burn across large portions of the landscape in any given year. In only three of the 290 years analysed did more than half of the sample sites synchronously record scars. The conifer forests of the SSPM are generally quite open when compared with similar present-day forests in California (Minnich *et al.*, 1995; Stephens & Gill, 2005). Average canopy cover is only 25% (range 14–50%; Stephens & Gill, 2005). Although very open, the stands are spatially complex, with groups or clusters of trees separated by more sparsely tree-covered areas (Stephens & Gill, 2005). Thus, it would be difficult for trees to cast sufficient needles in a way that would create a continuous cover of fuel (Fig. 11). Additionally, loading of woody fuels < 7.64 cm (primary carriers of fire other than needles) is quite low, with a heterogeneous spatial distribution similar to stand structure, and duff (fermentation + humus) layers are very thin or non-existent (Stephens, 2004). These factors, combined with too little grass to fill in wider openings between trees, suggest that wind and spotting may be important for achieving extensive fire spread. Thus, fires may have tended to create fine-grained, patchy, often discontinuous patterns, intensely burning denser patches of saplings and poles, but otherwise burning as fires of low to moderate intensity (Minnich *et al.*, 2000a; Stephens *et al.*, 2003).

Figure 10 Photograph of Jeffrey pine-dominated Sierra San Pedro Mártir stands *c.* 2 km north of Vallecitos Meadow. Surface fuels are primarily needle cast with limited amounts of grass or woody fuels. Photo by Scott Stephens.

Figure 11 Photograph showing typical opening within Jeffrey pine/mixed conifer forests *c.* 3 km west of Vallecitos Meadow. Foreground opening and the rocky area behind the trees would serve to limit the spread of fires for years while sufficient needle cast build up following a fire. Photo by Scott Stephens.

The 20th century

The first half of the 1900s is one of the two periods of highest fire activity in our record. The only similar period was the last

several decades of the 1700s (Fig. 5). Both periods of high fire activity were followed by several decades of unusually low fire activity. As can be seen in Fig. 8, both shifts from high fire activity to low fire activity were accompanied by strong positive to negative shifts in the combined PDO_B + NINO3 index as well as a decline in summer temperature (Briffa *et al.*, 2002).

Fire suppression activities, beginning in 1970, may be having a significant impact on the fire regimes of the SSPM. The major shift from positive to negative PDO_B + NINO3 that occurred in the mid-20th century was accompanied by widespread fires during the transition. However, although a few larger fires have occurred in the SSPM since 1946, none were detected on our plots as extensive fires. Additionally, the length of time without fires since 1946 is unusual in the SSPM fire record (Stephens *et al.*, 2003). Although the fire suppression forces are minimal, consisting of crews working with hand tools, their capability to disrupt the fire regime would be similar to the effect of crews on horseback that had such a strong influence on fire regimes in ponderosa pine and mixed conifer forests of the western USA in the very early part of the 20th century (e.g. Agee, 1993; Skinner & Chang, 1996; Arno & Allison-Bunnell, 2002). Although fire suppression activities are not as intensive as in similar forests in the USA, and have been in place for only a few decades, we may be seeing the beginning of a change in SSPM fire regimes similar to that receiving so much recent attention in the western USA.

CONCLUSIONS

Climate, both at local and regional scales, has strongly influenced the temporal and spatial variation of the characteristics of the fire regime in the conifer forests of the SSPM. The resulting fire regime is not stationary and defies simple statistical descriptions (e.g. mean, median FRIs, rotation, etc.) for periods longer than a few decades (Fig. 5). These complex interactions of fire and climate have helped to create diverse forest structures (Stephens & Gill, 2005) and heterogeneous patterns of forest fuels (Stephens, 2004). Although the fire regime in the SSPM varied more than many regimes described for the western USA, fires were mostly of low to moderate intensity and in most years were small and localized. Only in very dry years that occurred during major shifts in both PDO and ENSO, and that were preceded by 5–6 years of favourable growing conditions, did fires burn over extensive areas in the SSPM. Even in those years, there was considerable heterogeneity in burn pattern, with no year found in which all sample plots recorded a fire in the same year.

The implementation of a fire suppression programme over the past several decades, although still of limited intensity, has the potential to create profound changes in the fire regimes of the SSPM. These changes are likely to be accompanied by ecological changes (i.e. stand structure, species composition, fuel continuity, etc.) and associated management problems analogous to those that have occurred in similar forests of the western USA (e.g. Arno & Allison-Bunnell, 2002).

Barring an increase in the intensity of fire suppression activities, it will be important to continue to study the responses of the SSPM fire regime to climatic change, as it is one of the few functioning landscape-scale fire regimes in the North American mediterranean climate area.

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